Theory of the hadron (baryon) spectrum

- Missing resonances, N* program at Jlab
- Unitary, multi-channel analysis
- Competing models of the short-distance qq interaction
  - Can this issue be resolved by examining mixing angles in S_{11} and D_{13} states?
- New insights from lattice QCD calculations
  - Flux tube potential picture of $Q\bar{Q}$, QQQ
  - String breaking
  - Dramatic behavior of baryon masses in low m_π limit

Missing resonances

- Symmetric quark models predict many positive (and doubly-excited negative) parity states not seen in analyses of data
- PDG states were based on analyses of $N\pi$ elastic scattering
  - Are there states which couple weakly to $N\pi$?
  - These can be expected to be "missing"
  - **Evidence** for them should show up in other ($N\pi\pi$, ΛK,...) final states, excited with EM probes from nucleon targets (make N^* or Δ^*)
  - Their existence will be **established** in multi-channel analyses of many different final states

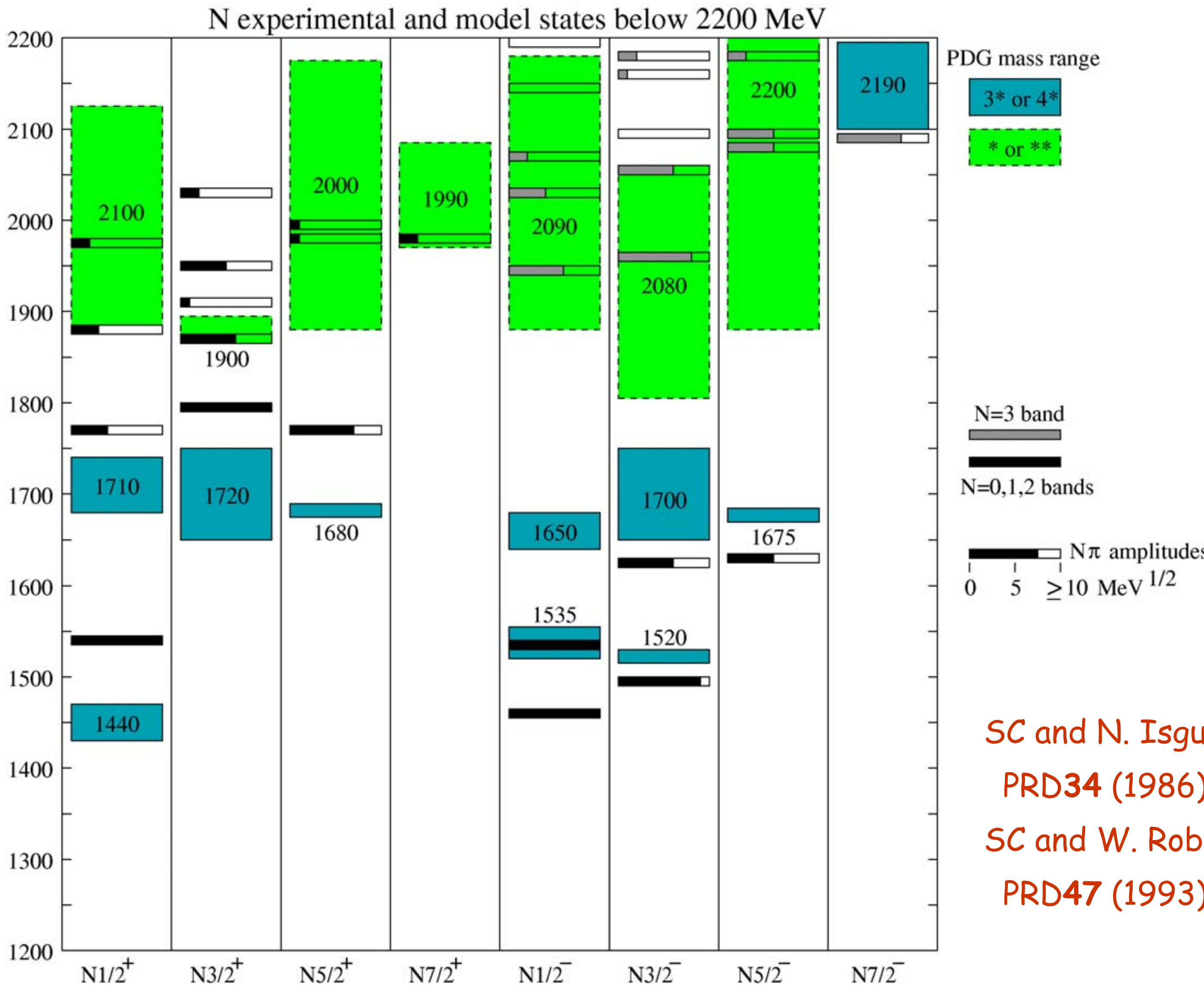
Missing resonances…

- R. Koniuk and N. Isgur
  - Elementary-meson emission decay model (quarks directly emit mesons)
  - Baryon structure from Isgur-Karl model

  ⇨ Showed missing states correspond in number and energy to those predicted to decouple from $N\pi$
- $^3P_0$: quark-pair creation decay model
  - Hadrons decay by creation of quark pair with quantum numbers of the vacuum
    - String breaking has same structure
  - Emitted mesons have structure
  - Baryons wave functions from structure model

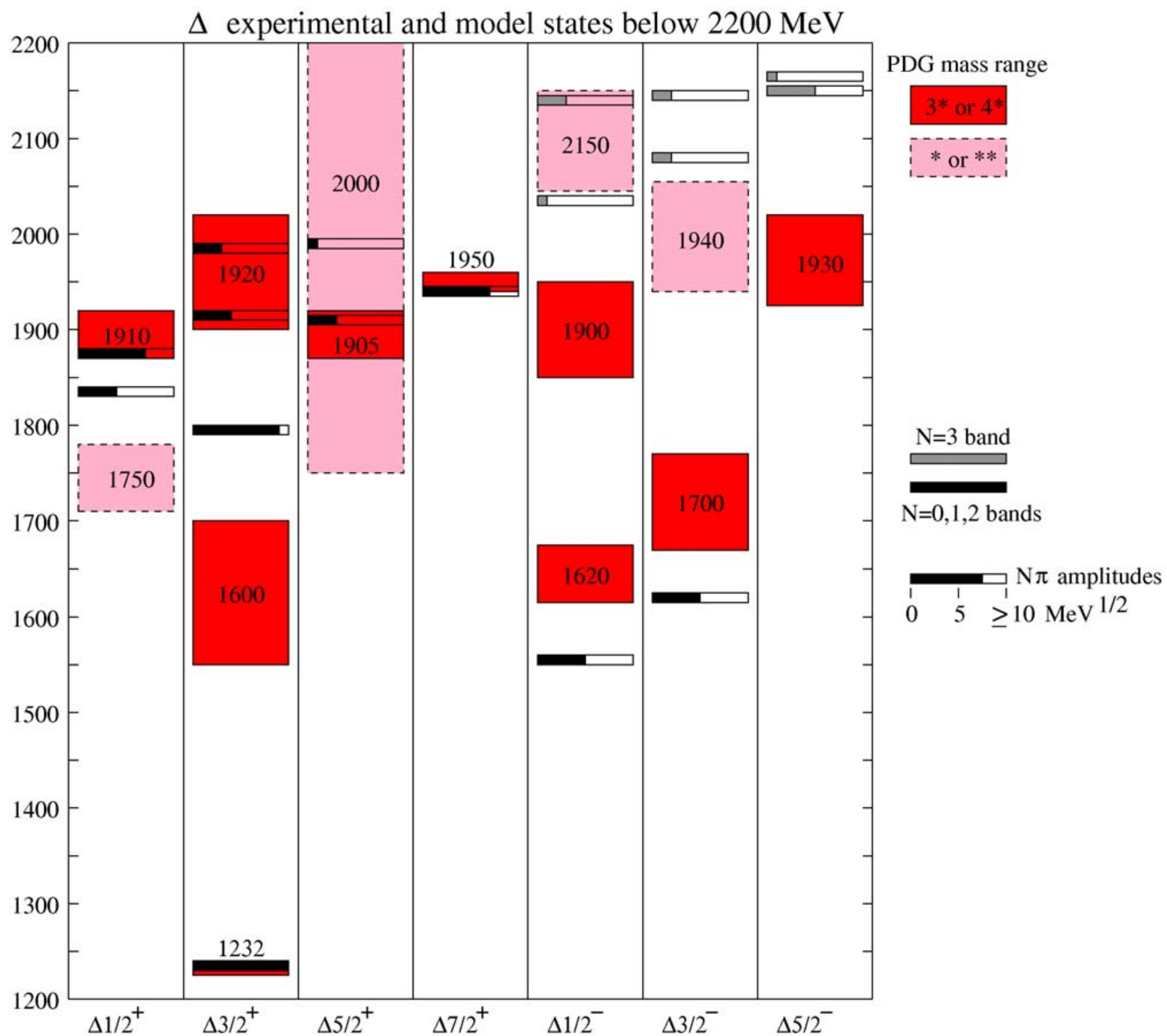
⇨ Can correlate many decays with a couple of parameters, predict which final states will show evidence of new states

Nucleon model states and Nπ couplings



SC and N. Isgur,
PRD**34** (1986) 2809;
SC and W. Roberts,
PRD**47** (1993) 2004

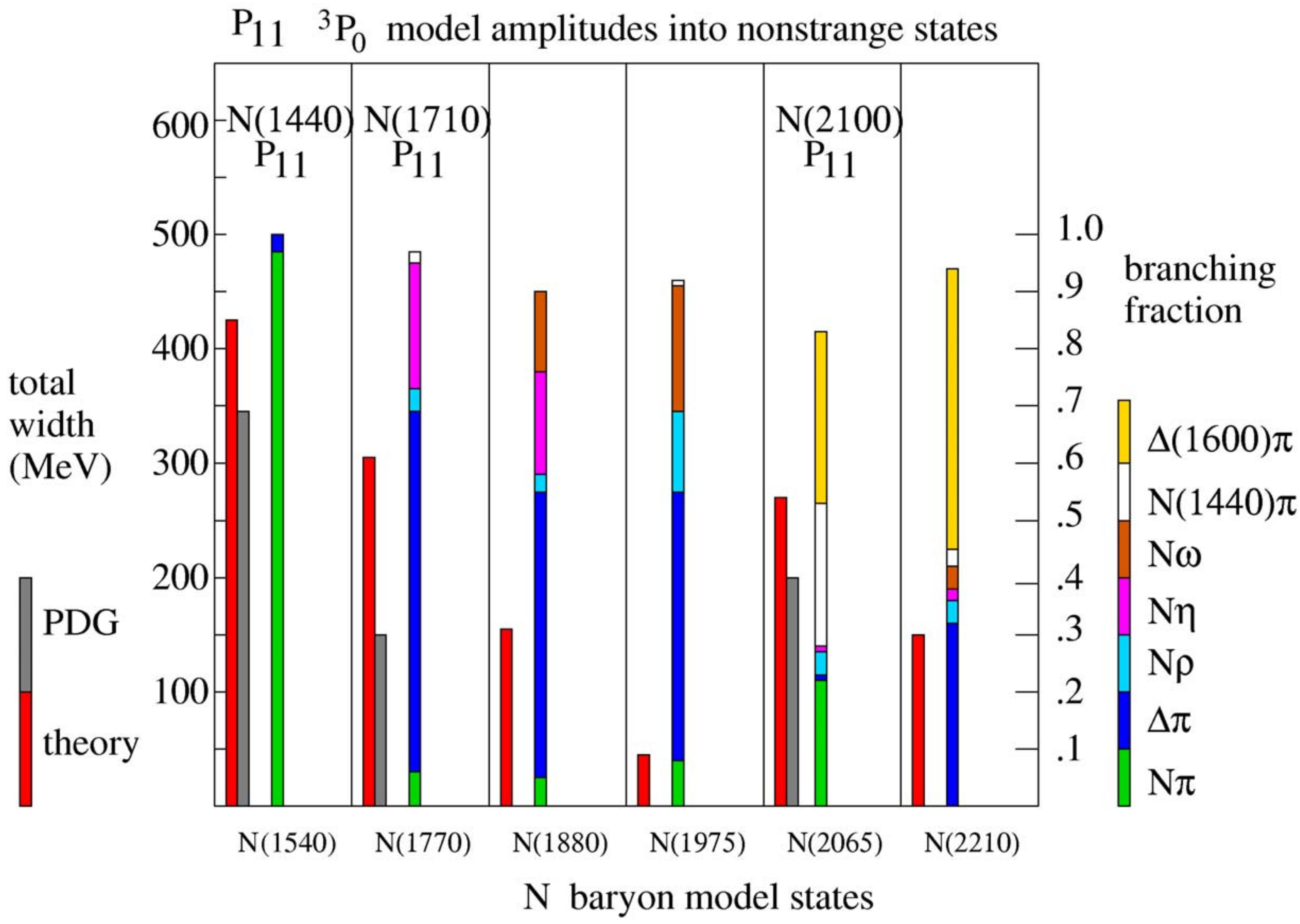
Δ model states and Nπ couplings



Predictions for branching fractions

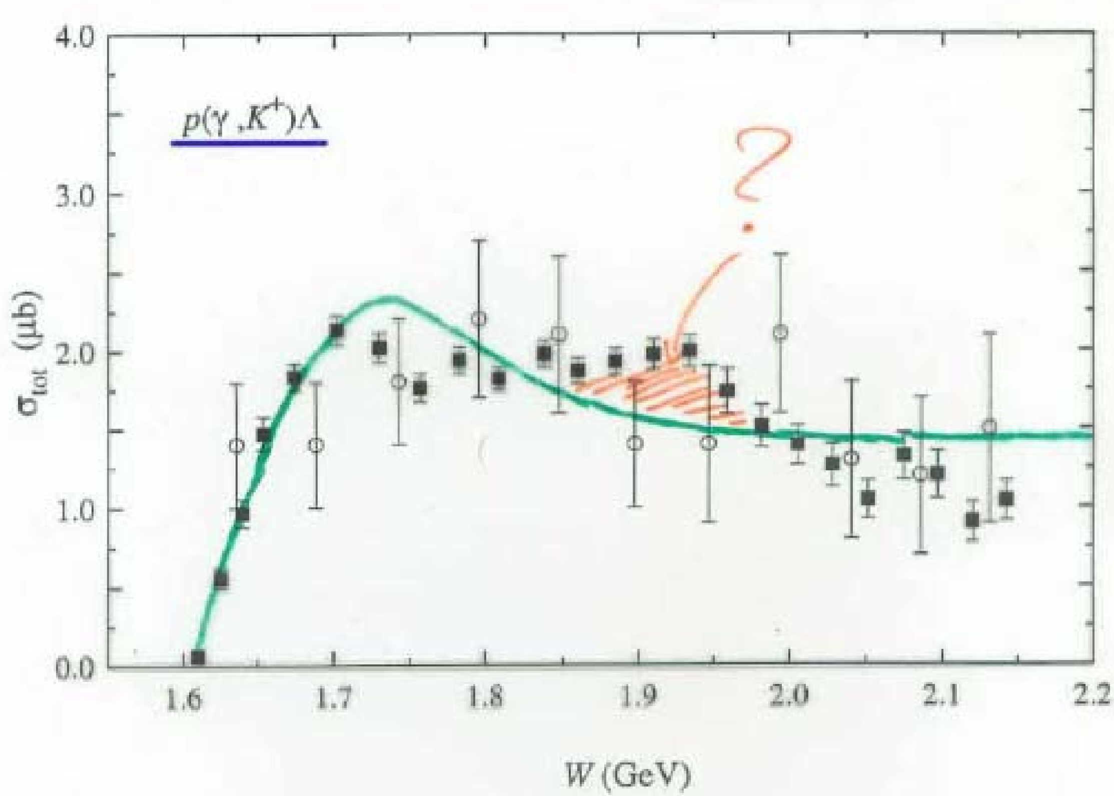
- Can calculate decay branching fractions if calculate enough decay channels!
  - Have looked at decays of N*, Δ* states to N, Δ, N(1440), Δ(1600)... and π, η, η′, ρ, ω
  - Also decays to strange final states, including Λ, Σ, Σ*, Λ(1405),... and K, K* (not shown below)

Predictions for branching fractions…



Have we seen new resonances?

- Effect seen in γp to ΛK^+ at W ~1900 MeV at SAPHIR; C. Bennhold et al.
  - Could be D_{13} predicted by model (has sizeable γN and ΛK coupling)
  - Or the effect of more than one state
- Need coupled channels to confirm



Have we seen new resonances?…

- Possible third S_{11} resonance at ~1.8 GeV
  - Rapidly rising cross section for γN to $N\eta$ above existing S_{11} states at GRAAL
  - Similar rise seen in CLAS in η photoproduction experiments
  - Very interesting possibility for quark models!
- Evidence from $N\rho$, $\Delta\pi$ electroproduction in CLAS that $P_{13}(1720)$ region not understood
  - Two states? Hard to fit in models…
- Huge potential for interesting new results from Jlab experiments!
  - Need multi-channel analysis to firmly establish new states

Unitary multi-channel analysis

- Based on K-matrix: KSU group, D.M. Manley and collaborators
- Effective Lagrangians: T. Sato and T.-S. H. Lee; GWU group: C. Bennhold, H. Haberzettl,...
- CMU-LBL (Cutkosky) method: Vrana, Dytman and Lee, Phys. Rept. **328**, (200), 181 (Pitt-ANL)
  - Extend $\pi N \Rightarrow \pi N$ **analysis** to many other channels
  - $N\pi$, $N\eta$, $N\gamma$, $N\rho$, $\Delta\pi$, $N\sigma$, ΛK, ΣK,...
  - Incorporate constraints from analyticity
  - Impose multi-channel unitarity

⇨ Resonance parameters are extracted from analysis of partial-wave amplitudes in all open channels simultaneously

Coupled Channel Picture of Resonance Excitation

- Each resonance can be reached through each asymptotic channel
- T matrix provides unitary, analytic structure
- all channels (e.g. πN, ρN) couple to all other channels in intermediate state
- photon multipoles ($E_{l\pm}$, $M_{l\pm}$) directly related to T

$$T(J^\pi) = \begin{pmatrix} T_{\pi N\to\pi N} & T_{\eta N\to\pi N} & T_{\gamma N\to\pi N} & T_{\rho N\to\pi N} & T_{\sigma N\to\pi N} & T_{K\Lambda\to\pi N} & T_{K\Sigma\to\pi N} \\ T_{\pi N\to\eta N} & T_{\eta N\to\eta N} & T_{\gamma N\to\eta N} & T_{\rho N\to\eta N} & T_{\sigma N\to\eta N} & T_{K\Lambda\to\eta N} & T_{K\Sigma\to\eta N} \\ T_{\pi N\to\gamma N} & T_{\eta N\to\gamma N} & T_{\gamma N\to\gamma N} & T_{\rho N\to\gamma N} & T_{\sigma N\to\gamma N} & T_{K\Lambda\to\gamma N} & T_{K\Sigma\to\gamma N} \\ T_{\pi N\to\rho N} & T_{\eta N\to\rho N} & T_{\gamma N\to\rho N} & T_{\rho N\to\rho N} & T_{\sigma N\to\rho N} & T_{K\Lambda\to\rho N} & T_{K\Sigma\to\rho N} \\ T_{\pi N\to\sigma N} & T_{\eta N\to\sigma N} & T_{\gamma N\to\sigma N} & T_{\rho N\to\sigma N} & T_{\sigma N\to\sigma N} & T_{K\Lambda\to\sigma N} & T_{K\Sigma\to\sigma N} \\ T_{\pi N\to K\Lambda} & T_{\eta N\to K\Lambda} & T_{\gamma N\to K\Lambda} & T_{\rho N\to K\Lambda} & T_{\sigma N\to K\Lambda} & T_{K\Lambda\to K\Lambda} & T_{K\Sigma\to K\Lambda} \\ T_{\pi N\to K\Sigma} & T_{\eta N\to K\Sigma} & T_{\gamma N\to K\Sigma} & T_{\rho N\to K\Sigma} & T_{\sigma N\to K\Lambda} & T_{K\Lambda\to K\Sigma} & T_{K\Sigma\to K\Sigma} \end{pmatrix}$$

Results of Pitt-ANL analysis

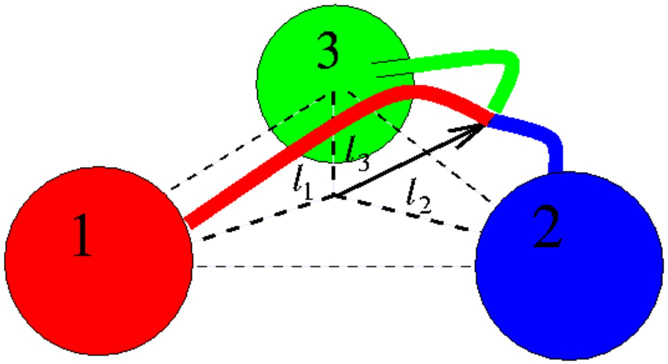
state	Mass (MeV)	Width (MeV)	$B_{N\pi}(\%)$	$B_{N\eta}(\%)$
$S_{11}(1535)$ (PDG)	1545(3) 1520-1555	127(19) 100-250	35(4) 35-55	55(5) 30-55
$S_{11}(1650)$ (PDG)	1693(12) 1640-1680	225(40) 145-190	73(2) 55-90	-2(1) 3-10
$D_{13}(1520)$ (PDG)	1520(3) 1515-1530	118(4) 110-135	61(2) 50-60	0(1)
$D_{13}(1700)$ (PDG)	1729(33) 1650-1750	178(133) 50-150	4(1) 5-15	7(1)

QCD-inspired models of baryons

- Work in adiabatic (Born-Oppenheimer) approximation
- Effect of glue is to generate qq potentials
  - Confining potential:
    - flux-tube?
    - Dirac structure in relativistic treatments?
  - Short-distance (residual) interactions
    - OGE model: link to meson and heavy-quark physics
    - OBE model: chiral symmetry dominates soft QCD spectrum
    - Instanton-induced model: QCD vacuum structure implies 't Hooft's instanton-induced interaction

Effective degrees of freedom

- One popular picture:
  - Constituent quarks
  - Glue in flux tubes (confinement)



⇨ Constituent quarks:

⇨ Dynamically generated constituent masses, which run with Q^2 : $m_{u,d} \approx K_{u,d} \approx \Lambda_{QCD} \approx 200$ MeV

⇨ Effective sizes, form factors

What are their residual interactions?

- Ground-state spectrum suggests flavor-dependent short-range (contact) interactions
- One-gluon exchange: good fit to ground states with (color-magnetic dipole-dipole), e.g. Δ–N, Σ-Λ
  ⇨DeRujula,Georgi,Glashow

$$M=\sum_{i=1}^{3} m_i+\frac{2\alpha_s}{3}\frac{8\pi}{3}\langle\delta^3(\mathbf{r})\rangle\sum_{i<j=1}^{3}\frac{\mathbf{S}_i\cdot\mathbf{S}_j}{m_i m_j}$$

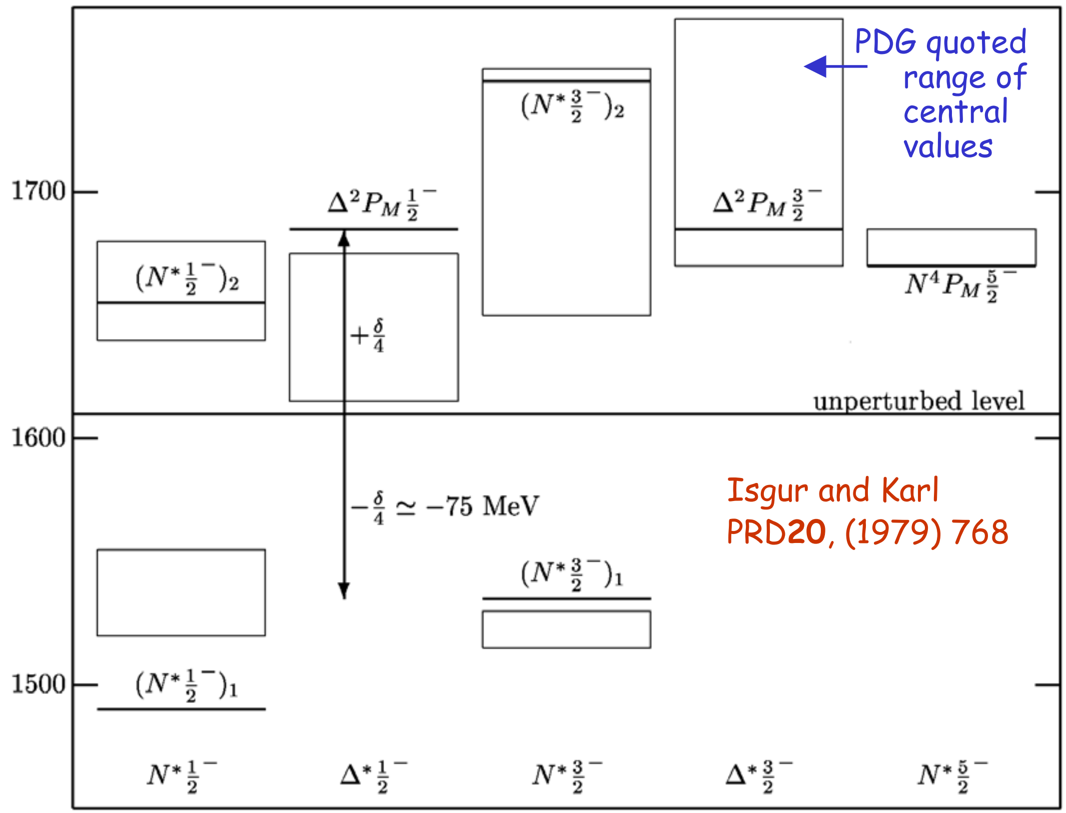
- Explains regularities in meson spectrum (e.g. evolution of vector-pseudoscalar splitting with quark mass)
  - Unclear why this should work for light quarks…
- Taken at face value predicts tensor interaction

$$H^{ij}_{\text{hyp}}=\frac{2\alpha_s}{3m_i m_j}\left\{\frac{8\pi}{3}\mathbf{S}_i\cdot\mathbf{S}_j\delta^3(\mathbf{r}_{ij})+\frac{1}{r_{ij}^3}\left[\frac{3(\mathbf{S}_i\cdot\mathbf{r}_{ij})(\mathbf{S}_j\cdot\mathbf{r}_{ij})}{r_{ij}^2}-\mathbf{S}_i\cdot\mathbf{S}_j\right]\right\}$$

- And spin-orbit interactions, at a level not present in spectrum

Residual interactions…

- Isgur and Karl PRD**20**, (1979) 768
- Contact splitting active in L=1 excited states
- Characteristic splitting is $(m_\Delta - m_N)/2$
- Add consistent tensor interaction
- No strong evidence for tensor from spectrum
- Best evidence from decays, $S_{11}(1535) \rightarrow N\eta$



Residual interactions…

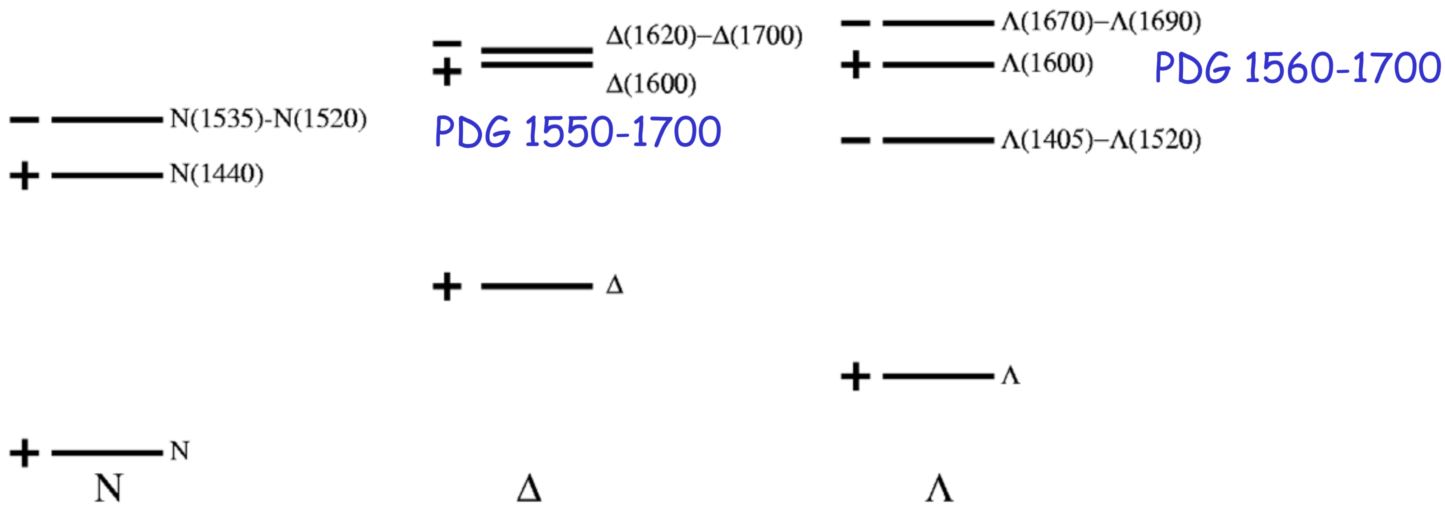
- Variational calculation in large HO basis (SC, N. Isgur)
  - String confinement, plus associated spin-orbit
  - Include OGE Coulomb, contact, tensor, spin-orbit
  - Relativistic KE, extended constituent quarks
  - parameterize momentum dependence, running coupling…

$$\left(\frac{m_i m_j}{E_i E_j}\right)^{\frac{1}{2}+\epsilon_{\rm cont}} \frac{8\pi}{3}\alpha_s(r_{ij})\frac{2}{3}\frac{\mathbf{S}_i\cdot\mathbf{S}_j}{m_i m_j}\left[\frac{\sigma_{ij}^3}{\pi^{\frac{3}{2}}}e^{-\sigma_{ij}^2 r_{ij}^2}\right]\left(\frac{m_i m_j}{E_i E_j}\right)^{\frac{1}{2}+\epsilon_{\rm cont}}$$

  - Photocouplings calculated with H_{int} expanded to $O(p^2/m^2)$
  - Strong decays calculated in pair creation ($^3P_0$) model (with W. Roberts)
- Reasonable agreement; allows prediction of favorable channels to find 'missing' baryons
- Puzzles: Roper mass; $\Lambda 3/2^-(1520)$-$\Lambda 1/2^-(1405)$; L=1 too light by 50 MeV, positive parity too massive by 50 MeV,…

Residual interactions…

- Another possibility: should light quarks exchange pions?
  Robson; Buchmann, Faessler,…
- Claim gluons not active in light-quark hadrons: flavor dependence through exchange of octet of pseudoscalars (GBE)
- Contact interaction: $$H_\chi \sim -\sum_{i<j} \frac{V(\mathbf{r}_{ij})}{m_i m_j} \boldsymbol{\lambda}_i^{\mathrm{F}} \cdot \boldsymbol{\lambda}_j^{\mathrm{F}} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j$$
- Order of states inverted? Natural with GBE
  - ⇨ Glozman & Riska (GR)

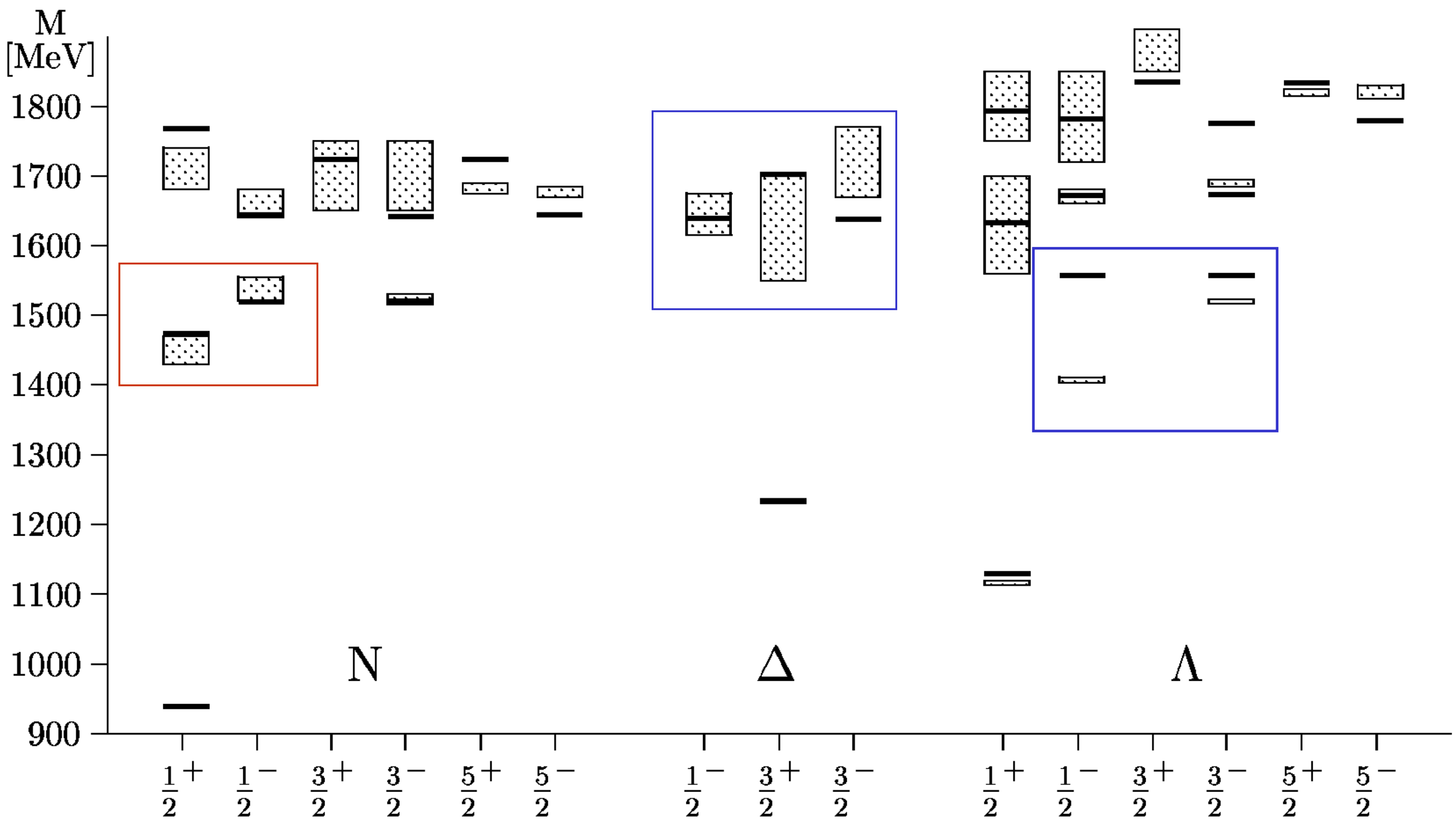


Residual interactions…

- GR fit radial matrix elements of $V(r_{ij})$ to spectrum
- **Calculated** in variational H.O. basis with consistent tensor Glozman, Plessas, Theussl, Wagenbrunn, & Varga
- Add nonets of exchange vector mesons and scalars
  - Relativistic K.E., string confinement; calculate decays
  - Problems can arise in some of these models with decays (poor results with OBE)
  - E.g. $N\eta$ decay of S11(1535) not possible without vector exchange added to GBE

Residual interactions…

- Results for spectrum:



Residual interactions…

- Another flavor-dependent possibility: instanton-induced interactions
- Present if qq in S-wave, I=0, S=0 state

$$\langle q^2; S, L, T | W | q^2; S, L, T \rangle = -4g\, \delta_{S,0}\, \delta_{L,0}\, \delta_{T,0} \mathcal{W}$$

- W is a contact interaction (has range λ)
  - causes no shifts in Δ^* masses
  - No tensor interaction, or spin-orbit forces
- Applied to excited states Blask, Bohn, Huber, Metsch & Petry
  - solve Bethe-Salpeter equation

Instanton-induced interactions

- Quarks confined by linear q-q potential

$$V(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3) = A_3 + B_3 \sum_{i<j} |\mathbf{r}_i - \mathbf{r}_j|$$

- Relativistic treatment, so need to choose Dirac structure of potential

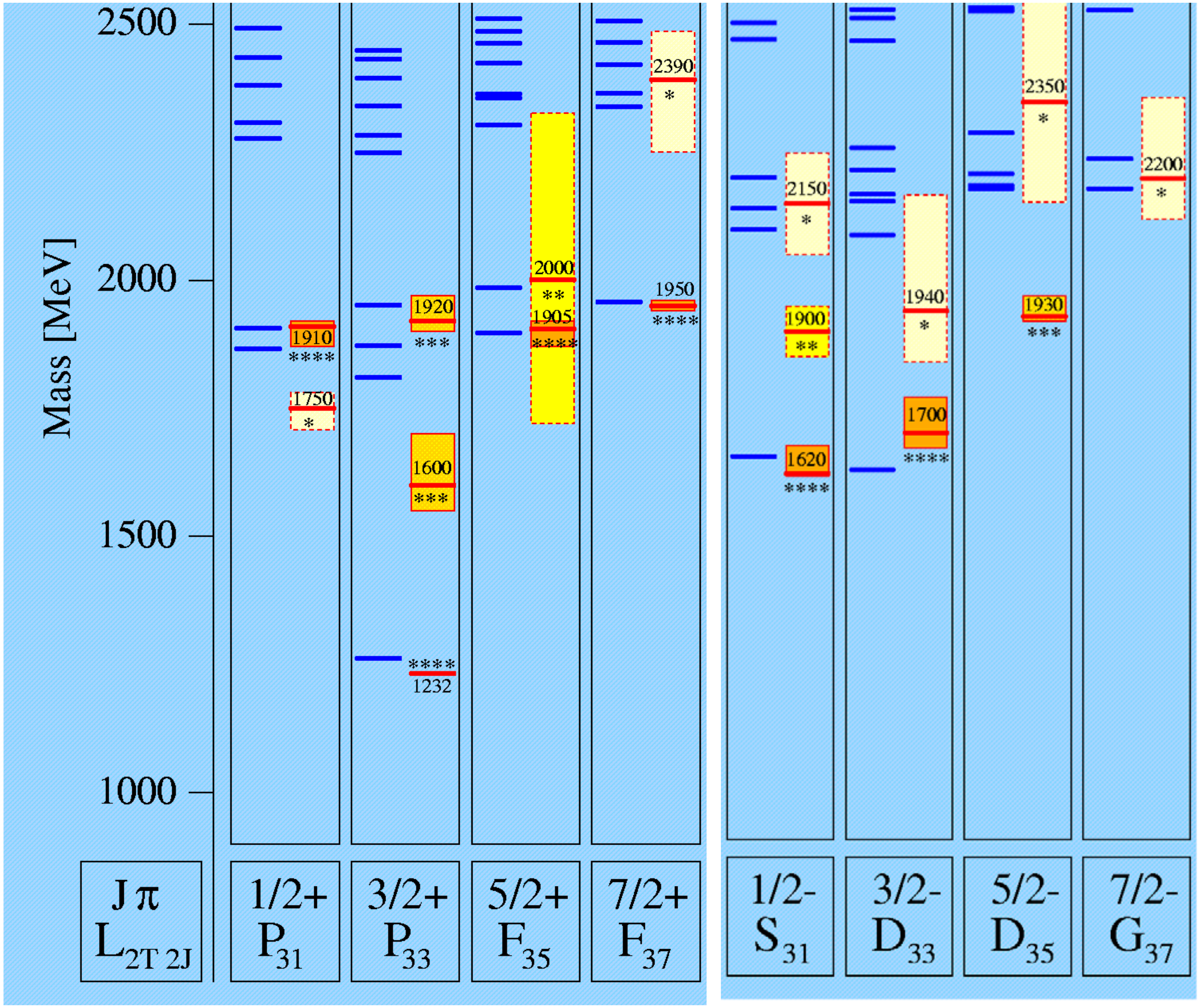
$$A_3 = a\,\frac{3}{4}\left[\mathbb{I}\otimes\mathbb{I}\otimes\mathbb{I}+\gamma^0\otimes\gamma^0\otimes\mathbb{I}+\gamma^0\otimes\mathbb{I}\otimes\gamma^0+\mathbb{I}\otimes\gamma^0\otimes\gamma^0\right]$$

$$B_3 = b\,\frac{1}{2}\left[-\mathbb{I}\otimes\mathbb{I}\otimes\mathbb{I}+\gamma^0\otimes\gamma^0\otimes\mathbb{I}+\gamma^0\otimes\mathbb{I}\otimes\gamma^0+\mathbb{I}\otimes\gamma^0\otimes\gamma^0\right]$$

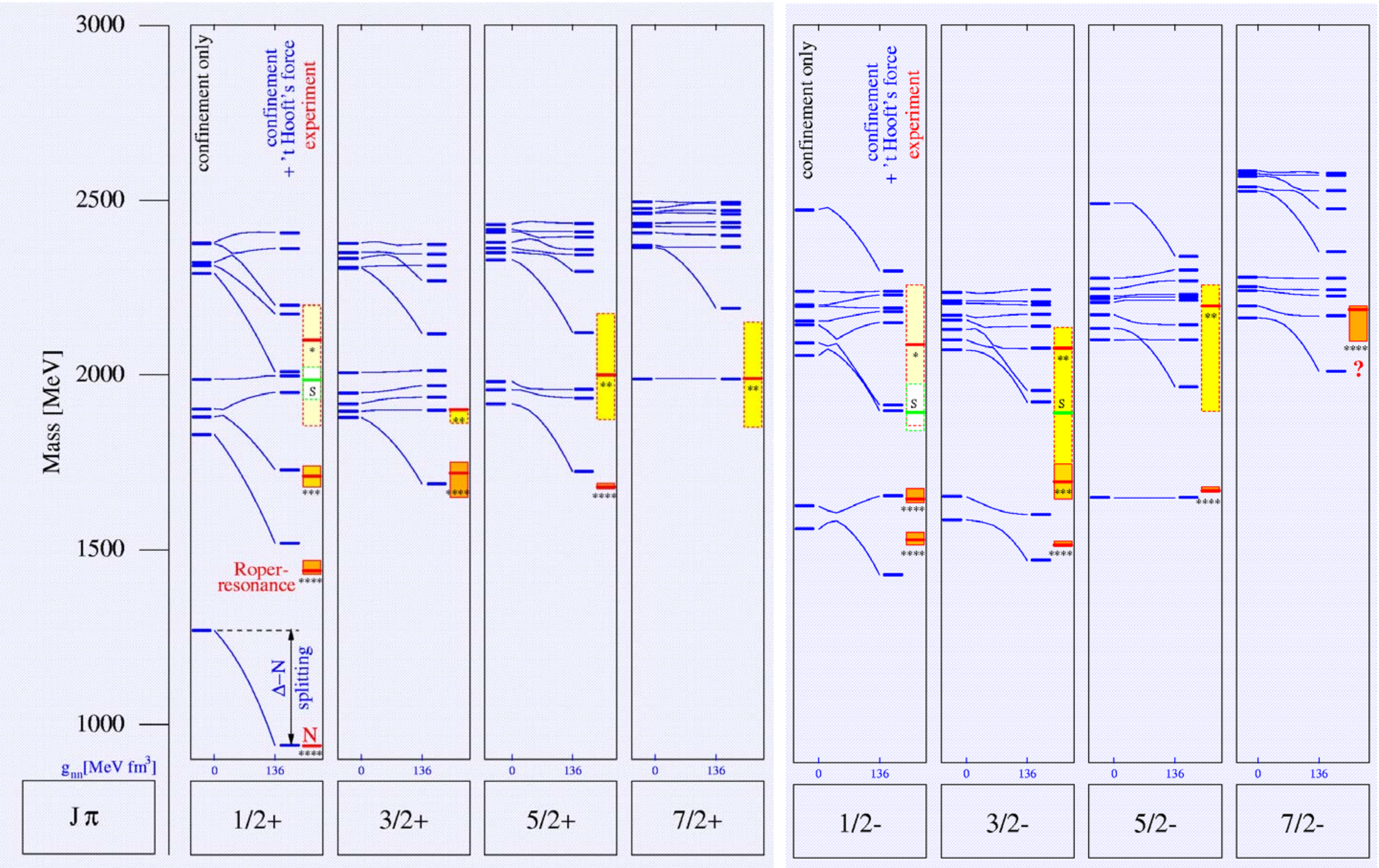
  - Chosen to reduce spin-orbit effects
  - Produces correct Regge trajectories
- For N*,D* only five parameters: m_n, g_{nn}, a, b, λ

Instanton-induced interactions…

- spectrum of Δ^* only from confining potential
- Blask, Bohn, Huber, Metsch & Petry



N* spectrum from 't Hooft's force



Nature of short-range qq interactions

- Spectrum alone cannot distinguish models
  - Wave functions much more sensitive
- Baryons have near degenerate excited states
    - two orbital spaces in 3q system, degenerate l=1 orbital excitations
    - two possible total quark spins
  - Degeneracy broken by spin-spin interactions (L=0 x S=0 operator)
  - Large mixing caused by tensor, spin-orbit,… interactions which must be present (relativity)

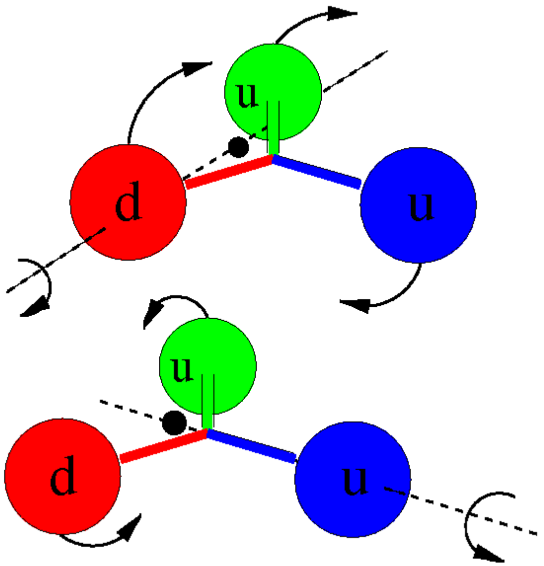
Why are mixing angles important?…

- Chizma and Karl, hep-ph/0210126
- Different effective interactions, adjusted to contact splittings, have very different tensor (and spin-orbit) interactions
  - Cause different mixing angles in low-lying S_{11} & D_{13} states

⇨ A determination of mixing angles can establish nature of effective interactions between quarks

Low lying excited baryons

- Negative-parity excited states
  $L^P = 1^- + S_{qqq}(1/2) = 1/2^-, 3/2^-$
  $L^P = 1^- + S_{qqq}(3/2) = 1/2^-, 3/2^-, 5/2^-$
- Orbital excitations in ρ or λ



- $2(N1/2^-, N3/2^-)$, $N5/2^-$, $D1/2^-$, $D3/2^-$
  - Two $N1/2^-$ model states, $S=1/2$ or $S=3/2$,
    - are S_{11} in $\pi N \Rightarrow \pi N$
    - resonances N(1535) and N(1650) in analyses
  - Two $N3/2^-$ states are D_{13} ⇨ N(1520), N(1700)

Low lying excited baryons…

- Without spin-dependent interactions between the quarks
  - Two degenerate S_{11} states ($S=1/2$ and $S=3/2$) and two degenerate D_{13} states
- Contact interactions breaks degeneracy
    - Proportional to $\Sigma_{i<j}\, \mathbf{S}_i \cdot \mathbf{S}_j\, f(r_{ij})$
  - Tensor and spin-orbit interactions **mix** two $S=1/2$ and $S=3/2$ states with same J^P

Mixing angles

- Physical states are admixtures of two possible L,S combinations

$$N(1535)1/2^- = \cos(\theta_S)\, N^2P1/2^- - \sin(\theta_S)\, N^4P1/2^-$$

$$N(1650)1/2^- = \sin(\theta_S)\, N^2P1/2^- + \cos(\theta_S)\, N^4P1/2^-$$

$$N(1520)3/2^- = \cos(\theta_D)\, N^2P3/2^- - \sin(\theta_D)\, N^4P3/2^-$$

$$N(1700)3/2^- = \sin(\theta_D)\, N^2P3/2^- + \cos(\theta_D)\, N^4P3/2^-$$

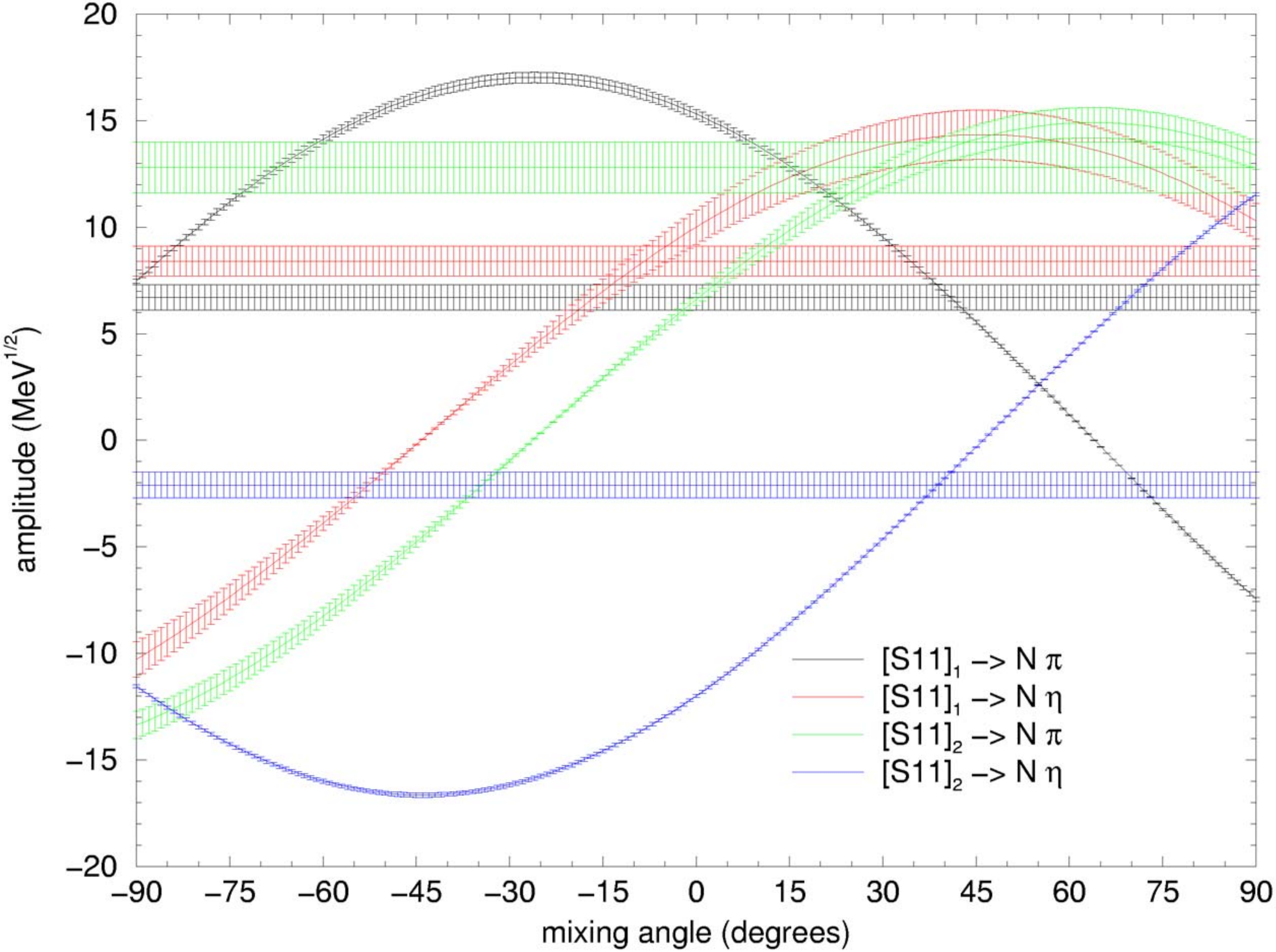
- How can θ_S and θ_D be determined?
- Lattice QCD, with enough time (CPU and elapsed!) and clever choice of correlators… or model of baryon structure and strong decays

Unmixed model states

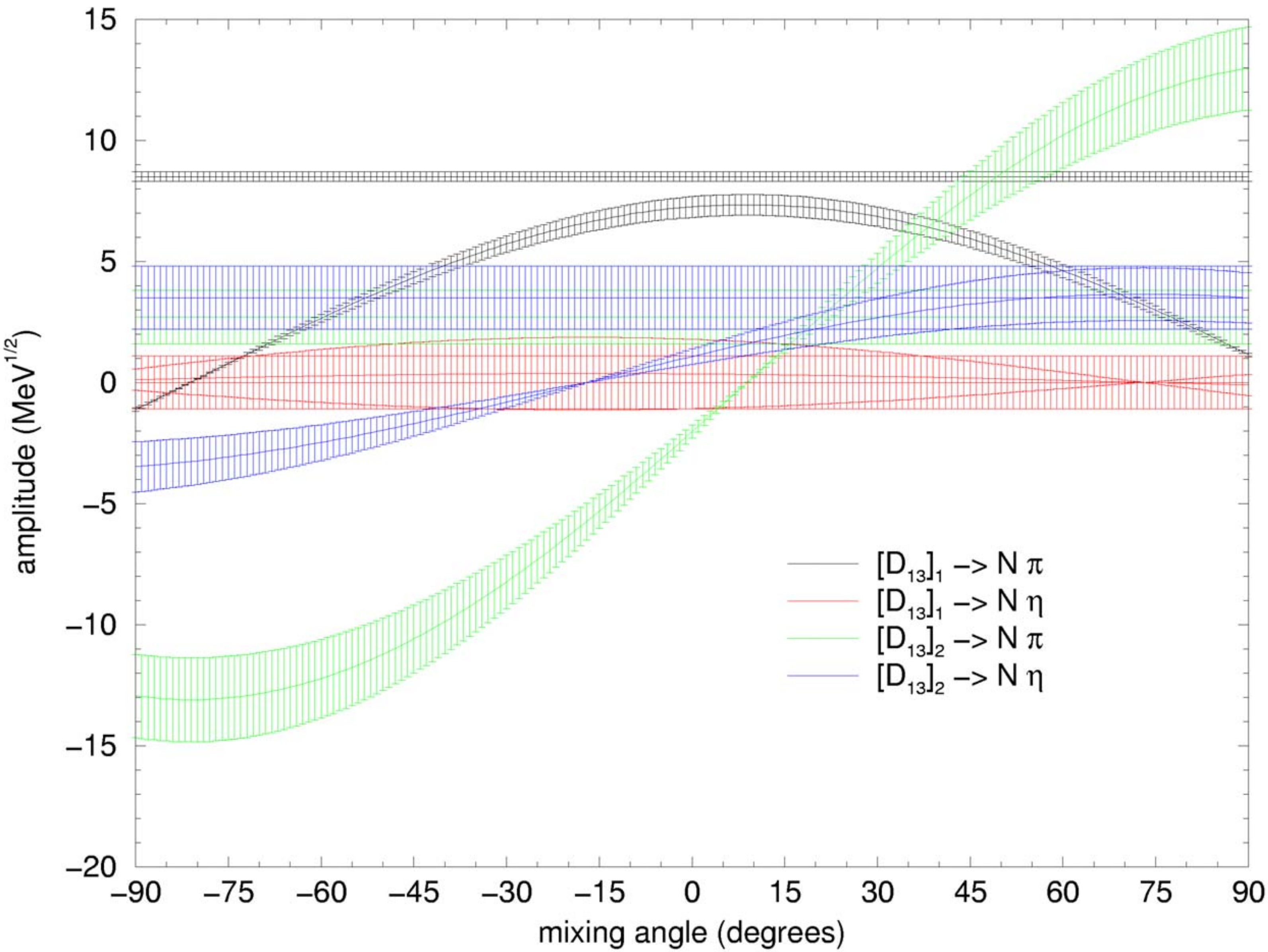
- Work done with W. Roberts (Jlab/ODU)
- Variational calculation in large HO basis
  - Unmixed states are orthogonal eigenstates of H, with definite L(=1) and S_{qqq} (1/2 or 3/2)
- OGE contact and color-Coulomb interactions
  - Turn off any interactions which are not simultaneous spin and spatial scalars
  - No tensor, spin-orbit (from confinement, OGE)

Decay model

- Use $^3P_0$, phenomenological decay model
  - Calculate decay amplitudes of unmixed states to $N\pi$, $N\eta$, ΛK
- Find decay amplitudes as a function of θ_S and θ_D
- Compare to Pitt-ANL analysis results



20
15
10
5
0
−5
−10
−15
−20
amplitude (MeV$^{1/2}$)
−90
−75
−60
−45
−30
−15
0
15
30
45
60
75
90
mixing angle (degrees)
[S11]$_1$ –> N π
[S11]$_1$ –> N η
[S11]$_2$ –> N π
[S11]$_2$ –> N η



15
10
5
0
−5
−10
−15
−20
−90
−75
−60
−45
−30
−15
0
15
30
45
60
75
90
amplitude (MeV$^{1/2}$)
mixing angle (degrees)
$[D_{13}]_1$ –> N π
$[D_{13}]_1$ –> N η
$[D_{13}]_2$ –> N π
$[D_{13}]_2$ –> N η

Extracted mixing angles

	$[\ ]_1 \Rightarrow \pi N$	$[\ ]_2 \Rightarrow \pi N$	$[\ ]_1 \Rightarrow \eta N$	$[\ ]_2 \Rightarrow \eta N$	$[\ ]_2 \Rightarrow \Lambda K$
θ_S	41^o	33^o	-8^o	39^o	$\sim 20^o$
θ_D	9^o	21^o		$>11^o$	

- Model does not fully describe $S_{11}(1535) \Rightarrow \eta N$
- Mixing angles $\theta_S \sim 35\text{-}40^o$, $\theta_D \sim 10\text{-}20^o$
- Other determinations: $\theta_S \sim 32^o$, $\theta_D \sim -10^o$
  - B. Saghai and Z. Li
  - Hey, Litchfield and Cashmore ('75)

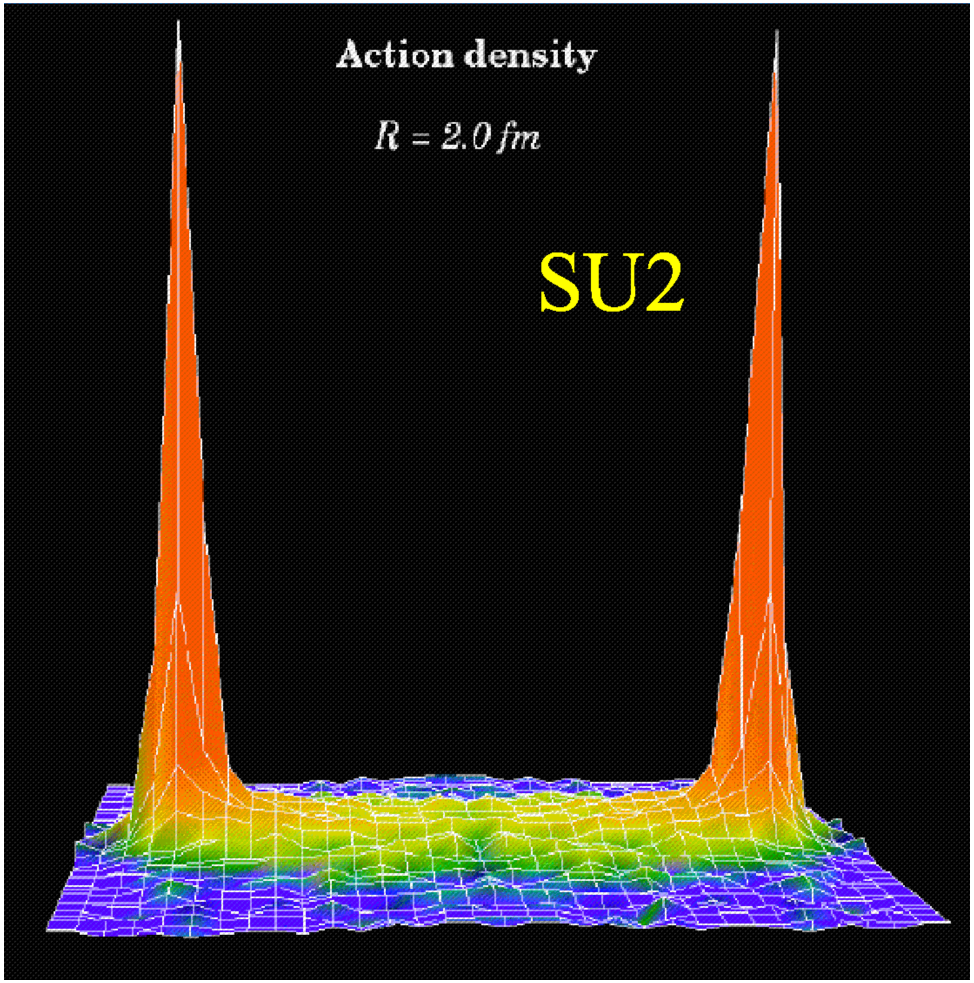
New insights from lattice QCD

- Is the potential model picture reasonable, at least for heavy-quark systems?

- Can lattice calculations explain the position of the light positive-parity states (like the Roper)?

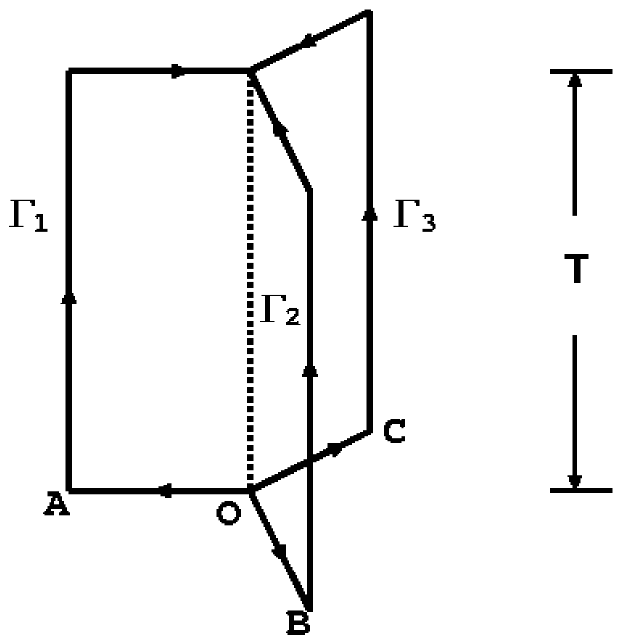
Confinement in heavy quark mesons

- Bali et al.
- Static quark and antiquark separated by 2 fm
- Gluonic flux shows tube structure between quarks



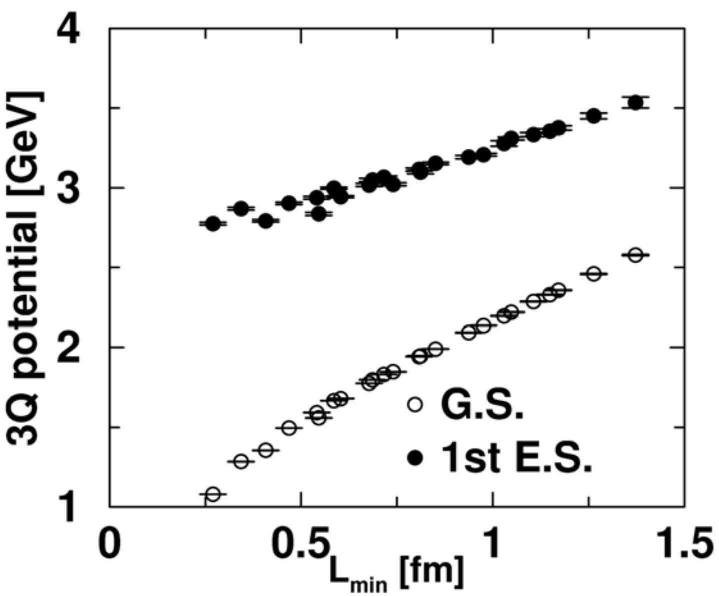
How should we treat confinement?

- Quenched lattice measurement of QQQ potential
- Takahashi, Matsufuru, Nemoto and Suganuma, PRL**86** (2001) 18.
- Measure potential with 3Q-Wilson loop (static quarks) for 0<t<T
- *Also fit* Q$\bar{Q}$ potential to compare σ and Coulomb terms

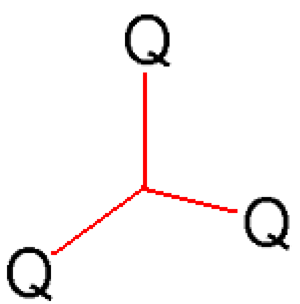


Confinement

- Quenched lattice calculation of QQQ static potential
  - Takahashi, Matsufuru, Nemoto and & Suganuma, PRL**86** (2001) 18, **hep-lat/0210024**
  - Plot vs. L_{min} = min. length Y-shaped string for 24 configurations



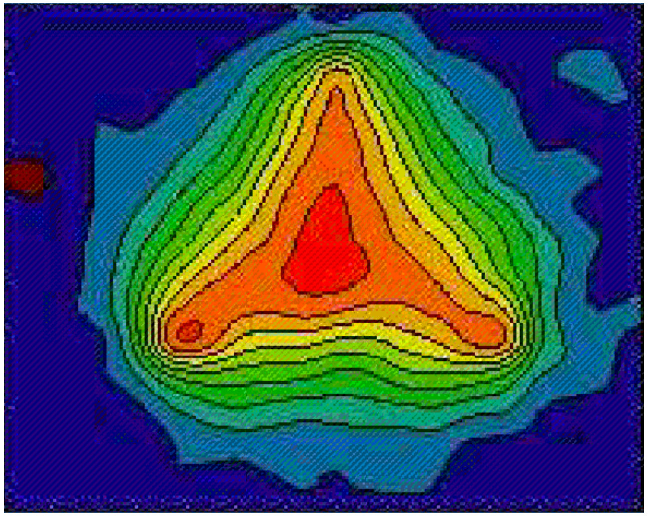
⇨ String-like flux-tube potential in QQQ baryons

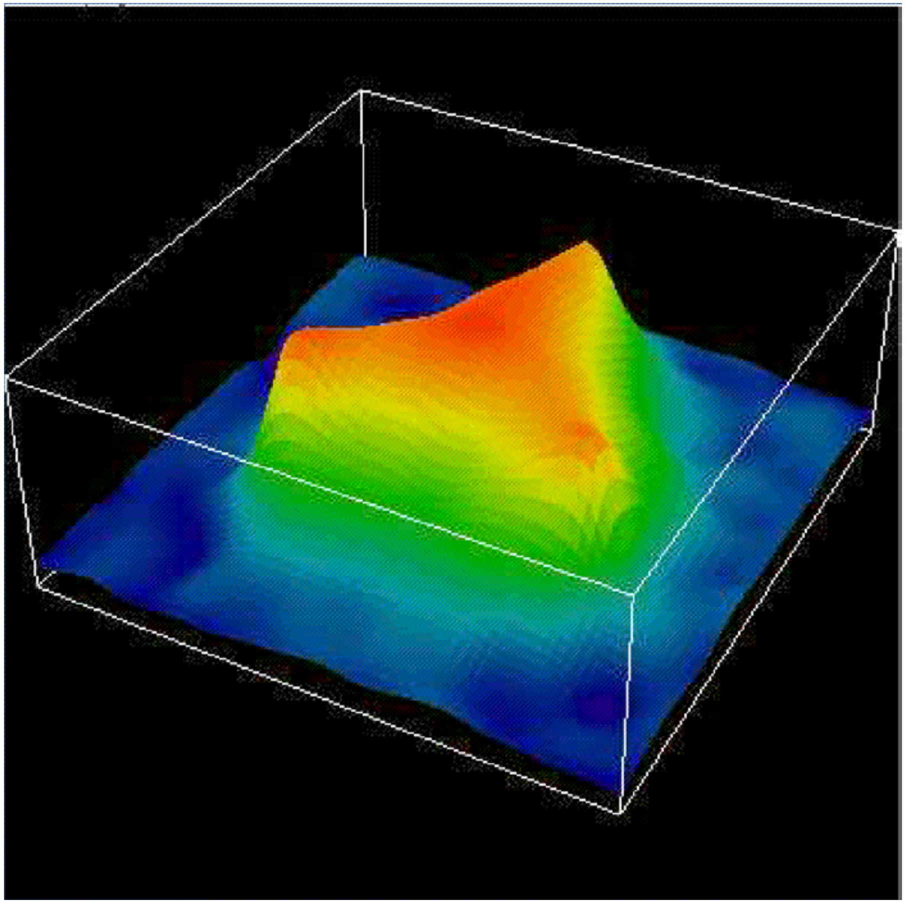


$$V_B(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)=\sigma(l_1+l_2+l_3)=\sigma L_{min}$$

Flux tube in QQQ baryons

- Abelian action distribution of gluons and light quarks nr. QQQ
- Ichie, Bornyakov, Struer & Schierholz, hep-lat/0212024





Leading Born-Oppenheimer approximation

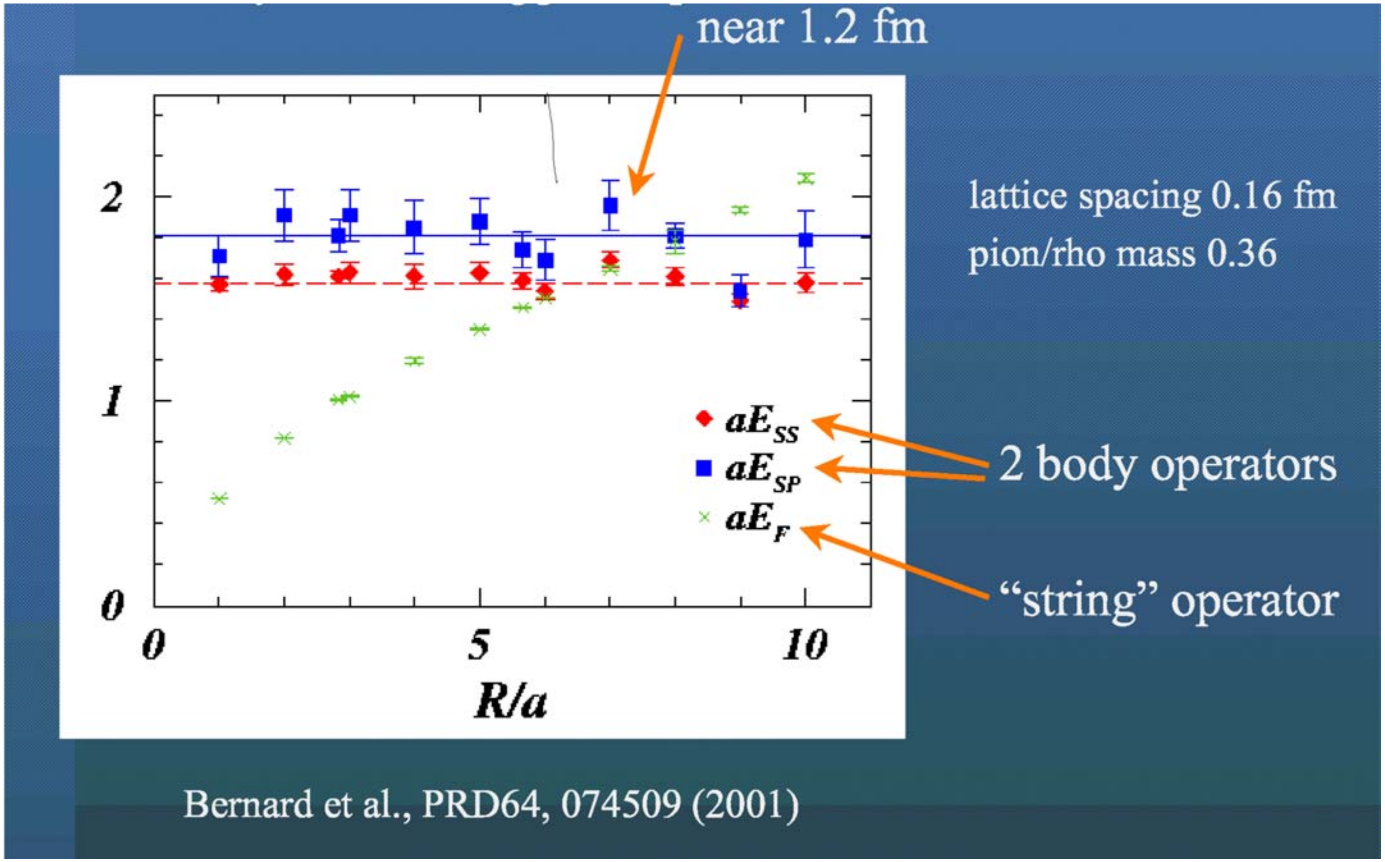
- Juge, Kuti, Morningstar PRL82, 4400 ('99)
  - Born Oppenheimer approximation for heavy-quark mesons
  - Use heavy-quark adiabatic potentials from lattice, including excited glue states
  - No light-quarks, no quark spin or retardation effects
- Compared to NRQCD results (Morningstar)
  - Retardation effects and mixing between states in different adiabatic potentials allowed

LBO approximation…

- Good agreement (10%) for level splittings of 4 conventional and 2 hybrid heavy-quark mesons
  - Partially explains success of constituent quark model
  - Allows inclusion of gluon dynamics
- Current LQCD studies:
  - Does LBO survive inclusion of quark spin?
  - OK, but worse in charmonium than upsilon
    - Drummond et al PLB478, 151 ('00)
    - Burch and Toussaint, hep-lat/0305008
  - Do light dynamical quarks spoil this picture?

Light quark effects on potential?

- Explore string breaking using two-body operators
- Allow two flavors of dynamical staggered quarks



Baryon spectroscopy in lattice QCD

- Recent progress in understanding first excited states ($J^\pi=1/2^+, 1/2^-$)
  - If pion masses ~500 MeV, calculated masses $N1/2^+ < N1/2^- < N^*1/2^+$ with roughly equal spacing
    - Physical state at (940/1535/1440)
  - Problem with quenched approximation?
  - Problem with m_π (light quark masses) being too large?

Baryon spectroscopy in LQCD…

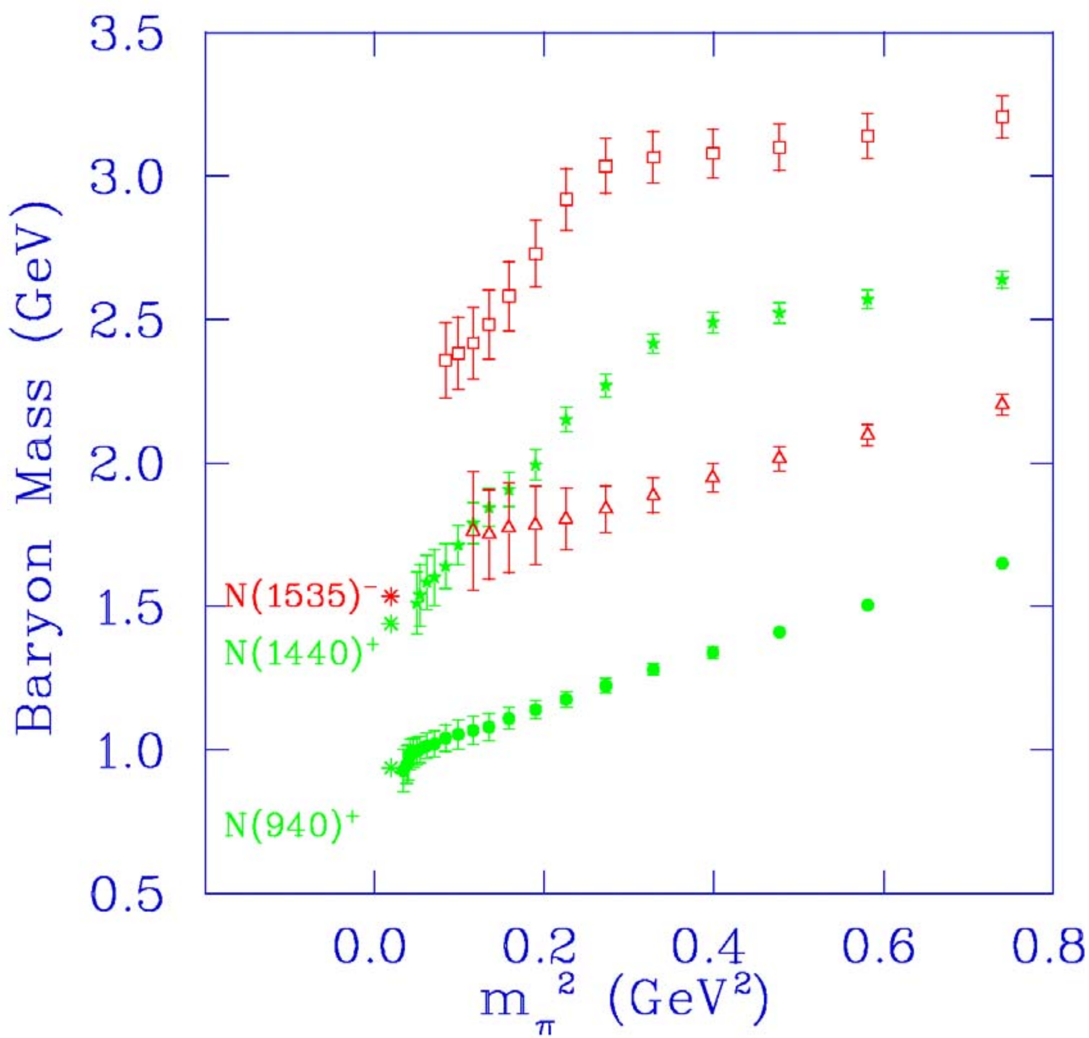
- C. Maynard, D.G. Richards (LHPC/UKQCD)
  - Show that this remains true in full (un-quenched) QCD at $m_\pi \sim 500$ MeV
- Light quarks (m_π):
  - Wilson fermions: $m_\pi \sim 400$ MeV
  - Smoothed actions (FLIC) $m_\pi \sim 300$ MeV
    - Have chiral symmetry only in $a \Rightarrow 0$ limit
- Overlap/domain wall fermions
  - Have exact analog of χ-symm. at finite a
  - Other physics and calculational advantages
  - But cost a factor of 30 in CPU time!

Light m_π baryon masses in LQCD

F. Lee et al. (Kentucky collaboration)

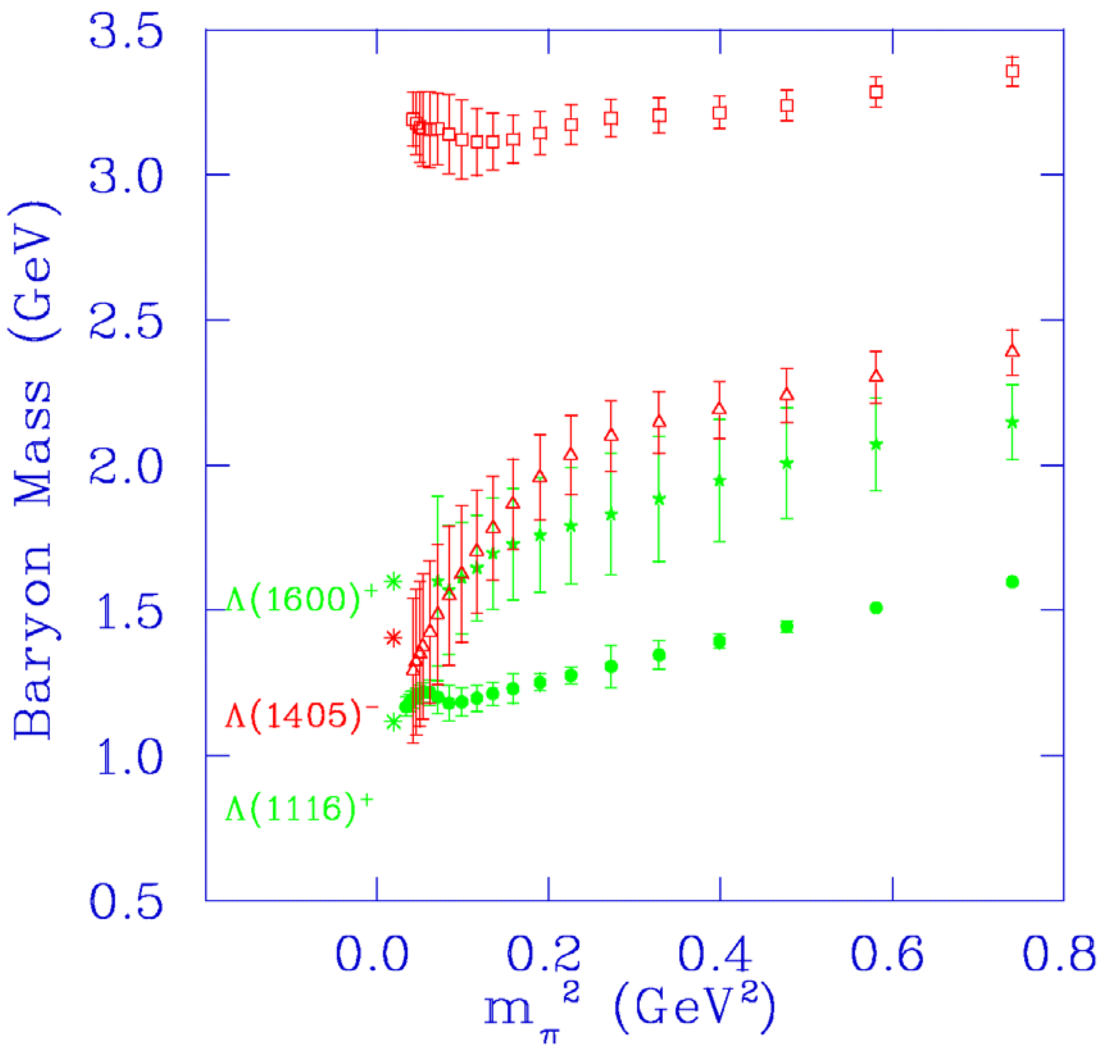
hep-lat/0208070

- Use overlap fermions and simple qqq operators
- Levels cross at low m_π



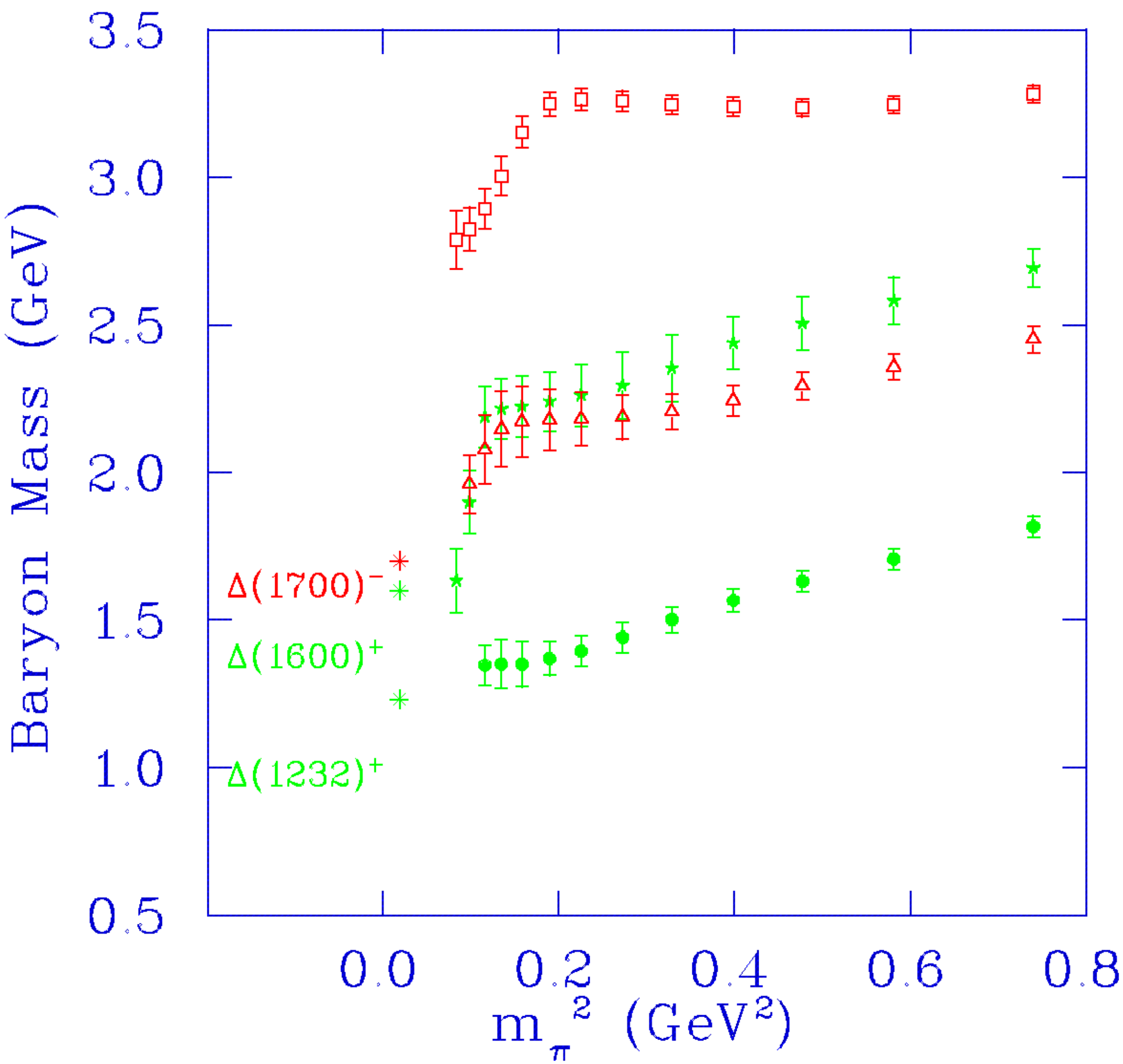
Light m_π baryon masses in LQCD…

- Same level crossing observed in light $\Lambda 1/2^+$ and $\Lambda 1/2^-$ states



Light m_π baryon masses in LQCD…

- *Also shows* approximate degeneracy of $\Delta^*3/2^+$ and $\Delta 3/2^-$



Baryon spectroscopy in LQCD…

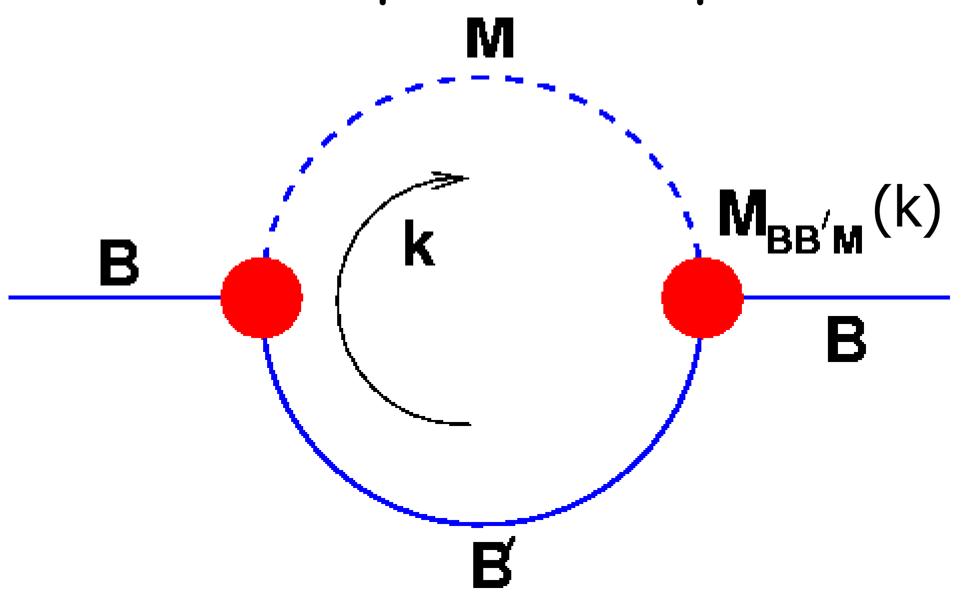
- Chiral behavior is important!
  - Non-analytic terms present in low m_π limit give rapidly varying behavior
  - Need to make (quenched) χ-PT extrapolations of lattice data to low m_π
- Roper likely a qqq state
  - Bare quark model qqq state should be too massive!
  - Couples strongly to $N\pi$ decay channel
  - Model with baryon-meson loops?
- Constituent quark model without loop effects will miss this important physics

Loop effects in baryon spectrum

- Two approaches:
  - Include elementary (bare) qqq excitations in careful calculation of reaction observables
    - Include rescattering into open B′M channels
    - S. Krewald, et al. (Juelich), T. Sato & H. Lee, C. Bennhold & GWU group
  - Explicitly evaluate hadron loop corrections to masses and decays
    - Mesons (ρ-ω): P. Geiger and N. Isgur

Unquenching the quark model

- In QCD qqq($q\bar{q}$) configurations possible in baryons: effect on CQM?
  - Model with baryon-meson intermediate states, loops ⇨ self energies: Danielle Morel & SC
  - High-momentum part of loops contains OBE



Unquenching the quark model…

- Hecht, Roberts, Tandy, Thomas,…
  - Schwinger-Dyson Bethe-Salpeter study
  - examine m_π dependence of $N\pi$ loop contribution to nucleon mass
- D. Morel and A.Thomas
  - Studying m_π dependence of contributions to resonance masses from $N\pi$ & $\Delta\pi$,… loops
  - Non-analytic behavior in extrapolation of lattice data for baryon masses to light quark (pion) masses

Summary

- New data from JLab and elsewhere
  - Contains evidence for new (missing) baryon states
  - Refines our knowledge of existing states
- Unitary multi-channel analysis of this data
  - Will establish new states
  - Can distinguish between QCD-inspired models
- Dramatic new lattice calculations
  - Support flux-tube potential model picture, at least for heavy-quark hadrons
  - Point to importance of decay-channel couplings with light quarks

Summary…

- Challenges to theory:
  - Analysis of data in many channels:
    - Reduce ambiguities in analysis by incorporating constraints from:
      - Multi-channel unitarity, analyticity, gauge invariance,…
    - Efficient treatment of 'background' consistent with these constraints
  - Include effects of open channels in:
    - Lattice QCD calculations
    - Reaction models
    - QCD-inspired models